Preprint typeset using LaTeX style emulateapj v. 12/14/05

FROM SUPERMASSIVE BLACK HOLES TO DWARF ELLIPTICAL NUCLEI: A MASS CONTINUUM

Elizabeth H. Wehner and William E. Harris
Department of Physics & Astronomy, McMaster University and
Hamilton, ON L8S 4M1, Canada

ABSTRACT

Considerable evidence suggests that supermassive black holes reside at the centers of massive galactic bulges. At a lower galactic mass range, many dwarf galaxies contain extremely compact nuclei that structurally resemble massive globular clusters. We show that both these types of central massive objects (CMO's) define a single unbroken relation between CMO mass and the luminosity of their host galaxy spheroid. Equivalently, M_{CMO} is directly proportional to the host spheroid mass over 4 orders of magnitude. We note that this result has been simultaneously and independently identified by Côté et al. (2006), see also Ferrarese et al. (2006). We therefore suggest that the dE,N nuclei may be the low-mass analogs of supermassive black holes, and that these two types of CMO's may have both developed starting from similar initial formation processes. The overlap mass interval between the two types of CMO's is small, and suggests that for $M_{CMO} > 10^7 M_\odot$, the formation of a black hole was strongly favored, perhaps because the initial gas infall to the center was too rapid and violent for star formation to occur efficiently.

Subject headings: black hole physics — galaxies: bulges — galaxies: nuclei — galaxies: dwarf — galaxies: fundamental parameters

1. INTRODUCTION

Even before the presence of supermassive black holes (SBH) was confirmed in galactic centers (Kormendy & Richstone 1995), studies of how these dark massive objects relate to their host galaxies were underway (see Ferrarese & Ford 2005, for a review). Kormendy & Richstone (1995) found that the masses of SBHs are correlated with the dynamical masses of the galactic bulges in which they reside. This correlation, along with others such as the $M_{BH} - \sigma$ relation (Gebhardt et al. 2000; Ferrarese & Merritt 2000) and $M_{BH} - L_{bulge}$ (Kormendy 1993; McLure & Dunlop 2002; Marconi & Hunt 2003; Bettoni et al. 2003) suggest that the formation of black holes is intricately linked with galaxy evolution and the early formation of the galaxy spheroid.

Magorrian et al. (1998) were the first to explore the $M_{BH} - M_{bulge}$ relationship in detail, finding that black hole mass goes up essentially in direct proportion to bulge mass, $M_{BH} \sim M_{sph}^{0.96}$. Later work by Häring & Rix (2004) improved the precision of previous discussions; their results are consistent with Magorrian et al. (1998), although they find a slightly higher slope 1.12±0.06. They also find that the $M_{BH} - M_{bulge}$ correlation is as tight as the more often explored $M_{BH} - \sigma$ relation.

What is less well known is whether this trend continues to lower masses. Observational searches for so-called intermediate-mass black holes (IBH) at the centers of smaller galaxies have been attempted, mostly without success, all the way down to the lowest-mass dwarf spheroidal satellites of the Milky Way (e.g. Valluri et al. 2005; Maccarone et al. 2005; Greene & Ho 2004). Well established cases with $M_{BH} < 10^7 M_\odot$ are extremely rare, the smallest one being the black hole in M32 at $M_{BH} = 2.5 \times 10^6 M_\odot$ (Verolme et al. 2002). It has been suggested that the small ($\sim 10^3 M_\odot$) black holes proposed to exist in some massive globular clusters such as M15 and M31-G1 may represent the low-end extrapolation of the $M_{BH} - M_{sph}$ relation (Gebhardt, Rich & Ho 2002; Gurkan, Freitag, & Rasio 2004). However, even if these GC-type black holes exist, they have formed within a stellar system of vastly different structure and smaller scale size than a galactic spheroid. Although galactic bulges and GCs are both "hot" stellar systems, they follow quite different fundamental-plane relations (e.g. Hasegan et al. 2005; McLaughlin & van der Marel 2005; Kissler-Patig, Jordán, & Bastian 2006, and numerous additional papers cited there): for E galaxies and bulges, the Faber-Jackson relation shows that luminosity scales with central velocity dispersion as $L \sim \sigma^4$, while GCs follow a relation closer to $L \sim \sigma^2$ (equivalent to nearly constant effective radius). The two sequences merge at the luminosity level of the "Ultra-Compact Dwarfs" (UCDs; cf. the references cited above).

However, small galaxies often contain another type of dense, massive system at their centers. A high fraction of dwarf elliptical galaxies in particular contain well defined, sharp nuclei: these are compact and (mostly) old stellar systems that have effective radii of a few parsecs, typically resembling massive globular clusters in size and structure (e.g. Durrell 1997; Miller et al. 1998; Lotz, Miller & Ferguson 2004; Geha, Guhathakurta, & van der Marel 2002; Grant, Kuipers, & Phillipps 2005). Some of the most massive known globular clusters such as NGC 6715, ω Cen, or M31-G1 are thought to be the relic nuclei of satellite dE,N galaxies that have been tidally stripped and absorbed by their bigger parents (e.g. Freeman 1993; Zinnecker et al. 1988; Layden & Sarajedini 2000; Majewski et al. 2000; Meylan et al. 2001; McWilliam & Smecker-Hane 2005). In turn, the dE,N nuclei themselves show no evidence for harboring massive black holes themselves (Geha, Guhathakurta, & van der Marel 2002) (while

Electronic address: wehnere@physics.mcmaster.ca, harris@physics.mcmaster.ca

their models suggest that BH formation is possible, they find only a generous dE,N black hole upper mass limit of $10^7 M_\odot$).

In this Letter, we explore the possibility that the dE,N nuclei may be the low-mass analogs of the SBHs found in more massive galaxies, and that there is a single mass continuum that connects these two types of central massive objects (CMOs).

2. THE $M_{CMO} - M_{SPHEROID}$ RELATION

In order to explore the more general link between a galaxy's central massive object (CMO) and its surrounding spheroidal component, we combine the relevant data in the literature for nucleated dwarf ellipticals and for galaxy bulges with SBHs. In Figure 1, we show the correlation between CMO masses and the luminosity of their surrounding spheroid: the dE,N nuclei data are taken from the high-resolution HST WFPC2 imaging of Lotz, Miller & Ferguson (2004), and the SBH data from the compilations of Ferrarese & Ford (2005) (SBH masses) and Tremaine et al. (2002) (spheroid data). (Although the SBH masses are more commonly plotted against the bulge velocity dispersion σ_{sph}, we cannot do this for more than a handful of the dE,N galaxies since only a few have measured $\sigma-$values. We therefore compare these two types of systems through their spheroid luminosities, which still give a well defined sequence.) For the dE,N nuclei, direct dynamical masses are not yet available for most of them, so we have calculated their masses by assuming a mass-to-light ratio appropriate for massive globular clusters, $(M/L) \simeq 3$; within factors of two, the general trend shown in Fig. 1 is quite insensitive to the adopted (M/L) of the nucleus.

Figure 1 shows that the two types of CMOs form a single continuous trend of increasing M_{CMO} with increasing host spheroid luminosity that seamlessly connects the dE nuclei with the SBH. There is, also, a fairly distinct break near $M_{CMO} \sim 10^7 M_\odot$, where the most luminous dE nuclei stop and the main population of SBHs begins. The small overlap between the two types of CMOs should only partly be due to observational selection effects: finding SBHs with $M < 10^7 M_\odot$ is challenging since they generate only small and subtle dynamical effects on their surrounding bulges; but any dE nuclei more luminous than $\sim 10^7 L_\odot$ would easily stand out observationally, and it seems plausible to conclude that they must be quite rare. While there is a change in slope at or near this transition point, the fact that these two object types, formerly thought to be unrelated, form a continuous sequence, suggests an interesting connection between these two populations.

For the SBHs, M_{CMO} scales closely in direct proportion to L_{sph}, as mentioned above. By contrast, Fig. 1 shows that the slope for the dE nuclei is distinctly flatter: Lotz, Miller & Ferguson (2004) do not quote a specific correlation, but a useful value is given by Grant, Kuipers, & Phillipps (2005), who find from their (B, I) photometry of dE,N galaxies in Virgo an overall scaling of $L_{nuc} \sim L_{dE}^{0.7}$. However, for progressively lower-luminosity dE galaxies, it is well known that their *luminosity* becomes increasingly less representative of their total *mass*, because the dark-matter component becomes relatively more dominant. Intrinsic scatter aside, it is plausible to expect that the CMO mass might be most strongly determined by the depth of the potential well that it finds itself in; that is, by the total mass enclosed by the galaxy spheroid. A more informative way to replot the correlation in Fig. 1 might then be a graph of CMO mass versus spheroid mass.

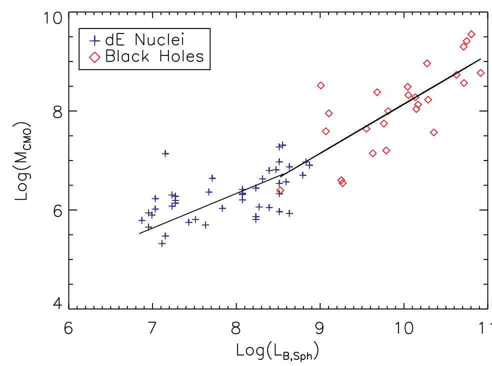

Fig. 1.— Log of the mass of the Central Massive Object (dE nucleus or central black hole) in a galaxy, $M_{CMO}/M_\odot$, plotted versus the log of the luminosity of the spheroid of the host galaxy, in Solar luminosities. Supermassive black holes are the open diamonds, while dE,N nuclei are the crosses. For the black holes, L_B refers to the total bulge luminosity of the galaxy, while for the dE,N nuclei, L_B refers to the luminosity of the entire dE. The line shown for the dE,N data represents the B-band slope of 0.7 measured by Grant, Kuipers, & Phillipps (2005).

In Figure 2, we show M_{CMO} versus the calculated values of M_{sph}. For the large-galaxy bulges, we have calculated total masses from their published magnitudes and their mass-to-light ratio (M/L). Tremaine et al. (2002) include bulge (M/L) data for most of their galaxies, which we used to obtain M_{sph} where possible. For those without listed M/L ratios, we used $M/L = 4.0$, the midpoint of the published values. These M/L ratios are derived from measured velocity dispersions in the hot component of the galaxy, and thus represent the total mass, from both luminous and dark matter, contained within the central spheroidal component of the galaxy. By employing the individual M/L values, we implicitly take into account any global trend of the mass-to-light ratios with galaxy luminosity; for example, for large ellipticals, the mass-to-light ratios scale roughly as $M/L \sim L^{0.3}$ (e.g. van der Marel 1991). The (M/L) values from Tremaine et al. (2002) agree well with this trend.

While published M/L data exist for numerous large galaxies and their spheroidal components, the literature for dE galaxies is not nearly so complete. Since so few dE velocity dispersions have been measured, we have used M/L to convert their luminosities into masses. According to cold dark matter theory, dwarf ellipticals form from average-amplitude density fluctuations in the early universe, and are dark matter dominated (Dekel & Silk 1986). There have been several subsequent efforts to measure the relationship between a galaxy's M/L ratio and its luminosity: If we write $(M/L) \sim L^{-\alpha}$, various recent results in the literature give α in the range $0.2 - 0.4$ (e.g. Dekel & Silk 1986; Peterson & Caldwell 1993; Mac Low & Ferrara 1999; Kormendy & Freeman 2004; De Rijcke et al. 2001). We adopt a scaling $\alpha \simeq 0.3$, and assume for the brightest dE's in the sample $(M/L) \simeq 5$ with the view that the combined stellar population of the largest dwarf E galaxies is closely similar to that of

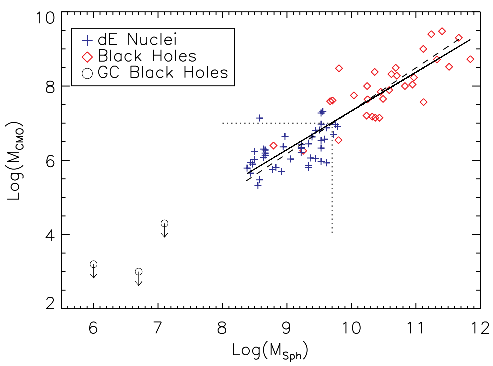

FIG. 2.— Log of the mass of the central massive object (dE nucleus or central black hole) versus the log of the mass of the old spheroidal component, both in Solar masses. The linear regression (solid) yields a slope of 1.04, supporting the idea that the direct correlation between $M_{BH} - M_{bulge}$ continues to lower masses. The average of the fits in X and Y is indicated by the dashed line. The dotted line marks the transitional potential-well mass, below which central SBH formation is inhibited. The globular cluster data (open circles) were taken from Kawakatu & Umemura (2005) and references therein.

the bulge of a bigger galaxy. This scaling then implies that the dE spheroid mass *including* the dark matter scales as $M_{sph} \sim L^{0.7}$, which is parallel to the relation between M_{CMO} and L in Fig. 1 above. This result immediately implies $M_{CMO} \sim M_{sph}^{1.0}$ for the dwarf galaxies.

A straightforward linear regression fit of M_{CMO} versus M_{sph} to the combined data in Fig. 2 yields

$$\log M_{CMO} = (1.04 \pm 0.06)\log M_{sph} - (3.10 \pm 0.60) \quad (1)$$

whereas a fit assuming the scatter to be distributed equally between the two quantities yields the dashed line in Figure 2, given by

$$\log M_{CMO} = (1.18 \pm 0.10)\log M_{sph} - (4.43 \pm 0.81) \quad (2)$$

The quoted uncertainties represent minimum 1σ errors. These fits are mutually consistent to well within their 2σ uncertainty. In summary, we find that the CMO mass in all these galaxies, defined either as the central black hole or the stellar-system nucleus, scales accurately in direct proportion to the surrounding mass of the spheroid over 4 orders of magnitude. We note that this trend has also been independently and simultaneously identified by Côté et al. (2006); Ferrarese et al. (2006).

For sake of completeness, we also include in Fig. 2 the upper limits for the suggested black hole masses in the globular clusters ω Cen, M15, and M31-G1 (Kawakatu & Umemura 2005, and references therein). As suggested by Gebhardt, Rich & Ho (2002) and Gurkan, Freitag, & Rasio (2004), they lie close to the $\sim 10^3 - 10^4 M_\odot$ black hole mass regime that would be expected from an extreme downward extrapolation of the SBH relation. As noted above, however, it is unclear whether they belong generically to the same sequence.

3. DISCUSSION

Although the connection we propose between SBHs and dE,N nuclei rests on some indirect argument, the unbroken continuum shown in the Figures, regardless of modest slope changes, is highly suggestive that both types of objects may represent two possible endpoints of a similar initial formation process. Both types of objects are at the deepest points in their surrounding large-scale potential wells, and both are suggested to be quite old; that is, they were among the first substructures to have formed within the initial spheroid of the host galaxy (e.g. Lotz, Miller & Ferguson 2004; Ferrarese 2002).

We suggest that the key factor deciding whether a CMO would end up as either a supermassive black hole or a globular-cluster-like stellar system may have been the rapidity of the initial gas infall rate to the center. This, in turn, will be driven by the depth of the large-scale potential well of the young host galaxy. For gas gravitating within the dark-matter halo of the spheroid, Haehnelt, Natarajan, & Rees (1998) find that the mass deposition rate at the center will increase with the halo circular velocity as $\dot{M} \sim v^3$, or equivalently (Ferrarese 2002) $\dot{M} \sim M_{DM}$. Evidently, for the highest-mass bulges, gas falls in rapidly and violently, favoring the formation of a black hole and quick initial growth. It seems reasonable then to speculate that for smaller galaxies with slower central accumulation rates, say timescales very roughly longer than $\sim 10^6$ years, the central gas mass would have time to make stars, halt any further inward dissipation and collapse of the gas, and settle into a subsystem strongly resembling a massive globular cluster or UCD.

If this speculation is essentially correct, then Figures 1 and 2 empirically identify the transition point where the CMO changes from a dE,N nucleus to a SBH. This mass occurs at approximately $M_{CMO} \simeq 10^7 M_\odot$ or equivalently $M_{sph} \simeq 10^{10} M_\odot$. Above that limit, formation of a SBH is strongly favored. Contrarily, galactic potential wells much smaller than this appear less likely to support the formation and growth of a central black hole; instead, the infalling gas generates a more familiar, though still very compact, stellar system. In this respect, the suggestions of Ferrarese (2002) that potential wells "... of mass smaller than $\sim 5 \times 10^{11} M_\odot$ are increasingly less efficient at forming SBHs – perhaps even unable to form them", and of Haehnelt, Natarajan, & Rees (1998) that "there might be a physically determined lower limit [above $10^6 M_\odot$] to the mass of a supermassive black hole" seem prescient. On the basis of the preceding arguments, we speculate that when it becomes possible to model this rapid central formation process more completely, the accumulation of $\sim 10^7 M_\odot$ of gas within a "transition" bulge mass of $\sim 5 \times 10^9 M_\odot$ will be found to take 10^6 years or less.

Our results are also more consistent with dE,N models in which the formation of the dwarf galaxy and its massive, distinct nucleus are linked and coeval. Lastly, we point out that this link may provide a physical reason for the long-observed upper mass limit of about $10^7 M_\odot$ for old globular clusters (e.g. Harris et al. 2006).

EHW and WEH thank the Natural Sciences and Engineering Research Council of Canada for financial support. We are grateful to Pat Côté and Laura Ferrarese for comments on an early version, and for cooperating with the publication process.

REFERENCES

Côté, P. et al. 2006, ApJS, accepted.
Bettoni, D., Falomo, R., Fasano, G., & Govoni, F. 2003, A&A, 399, 869
Dekel, A. & Silk, J. 1986, ApJ, 303, 39
De Rijcke, S., Dejonghe, H, Zeilinger, W. W., & Hau, G. K. T. 2001, ApJ, 559, L21
Durrell, P. R. 1997, AJ, 113, 531
Ferrarese, L. 2002, ApJ, 578, 90
Ferrarese, L. & Ford, H. 2005, SSRv, 116, 523
Ferrarese, L. & Merritt, D. 2000, ApJ, 539, L9
Ferrarese, L et al. 2006, ApJ, submitted.
Freeman, K. C. 1993, in ASP Conf. Ser. 48, The Globular ClusterGalaxy Connection, ed. G. H. Smith & J. P. Brodie (San Francisco: ASP), 608
Gebhardt, K., et al. 2000, ApJ, 539, L13
Gebhardt, K., Rich, R. M., & Ho, L. C. 2002,
Gebhardt, K. et al. 2003, ApJ, 583, 92 ApJ, 578, L41
Grant, N. I., Kuipers, J. A, & Phillipps, S. 2005, MNRAS, 363, 1019
Geha, M., Guhathakurta, P., & van der Marel, R. P. 2002, AJ, 124, 3073
Greene, J. E., & Ho, L. C. 2004, ApJ, 610, 722
Gurkan, M. A., Freitag, M., & Rasio, F. A. 2004, ApJ, 604, 632
Haehnelt, M. G., Natarajan, P., & Rees, M J.1998, MNRAS, 300, 817
Häring, N. & Rix, H. 2004, ApJ, 604, L89
Harris, W. E., Whitmore, B. C., Karakla, D., Okon, W., Baum, W. A., Hanes, D. A., & Kavelaars, J. J. 2006, ApJ, 636, 90
Hasegan, M. et al. 2005, ApJ, 627, 203
Kawakatu, N. & Umemura, M. 2005, ApJ, 628, 721
King, A. 2003, ApJ, 596, L27
Kissler-Patig, M., Jordán, A., & Bastian, N. 2006, A&A, 448, 1031.
Kormendy, J. 1993, in The Nearest Active Galaxies, ed. J. Beckman, L. Colina, & H. Netzer (Madrid: Consejo Superior de Investigaciones Cientifícas), 197
Kormendy, J., & Freeman, K. C. 2004, IAU Symposium no. 220, ed. S. D. Ryder, D. J. Pisano, M. A. Walker, & K. C. Freeman (San Francisco: Astronomical Society of the Pacific), p.377
Kormendy, J. & Richstone, D. 1995, ARA&A, 33, 581
Layden, A. C., & Sarajedini, A. 2000, AJ, 119, 1760
Lotz, J. M., Miller, B. W., & Ferguson, H. C. 2004, ApJ, 613, 262
Mac Low, M.-M. & Ferrara, A. 1999, 513, 142
Maccarone, T. J., Fender, R. P., & Tzioumis, A. K. 2005, MNRAS, 356, L17
Magorrian, J., et al. 1998, AJ, 115, 2285
Majewski, S. R., Patterson, R. J., Dinescu, D. I., Johnson, W. Y., Ostheimer, J. C., Kunkel, W. E., & Palma, C. 2000, in The Galactic Halo: From Globular Cluster to Field Stars, ed. A. Noels, et al. (Liège: Inst. d'Astrophys. Géophys.), 619
Marconi, A. & Hunt, L. K. 2003, ApJ, 589, L21
McLaughlin, D. E., & van der Marel, R. 2005, ApJS, 161, 304
McLure, R. J. & Dunlop, J. S. 2002, MNRAS, 331, 795
McWilliam, A., & Smecker-Hane, T. A. 2005, ApJ, 622, L29
Meylan, G., Sarajedini, A., Jablonka, P., Djorgovski, S. G., Bridges, T., & Rich, R. M. 2001, AJ, 122, 830
Miller, B. W., Lotz, J. M., Ferguson, H. C., Stiavelli, M., & Whitmore, B. C. 1998, ApJ, 508, L133
Peterson, R. C., & Caldwell, N. 2003, AJ, 105, 1411
Tremaine, S. et al. 2002, ApJ, 574, 740
Valluri, M., Ferrarese, L., Merritt, D., &
van der Marel, R. P. 1991, MNRAS253, 710 Joseph, C. L. 2005, ApJ, 628, 137
Verolme, E. K. et al. 2002, MNRAS, 335, 517
Zinnecker, H., Keable, C. J., Dunlop, J. S., Cannon, R. D., & Griffiths, W. K. 1988, in IAU Symp. 126, The Harlow-Shapley Symposium on Globular Cluster Systems in Galaxies, ed. J. E. Grindlay & A. G. D. Philip (Dordrecht: Kluwer), 603